REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 10/30/05	3. REPORT TYPE AND DATES COVERED Final 05/15/03 to 06/14/05

4. TITLE AND SUBTITLE

Technology Development for Linear Optics Quantum Computing Program

5. FUNDING NUMBERS
DAAD19-03-1-0097

6. AUTHOR(S)
J.D. Franson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Johns Hopkins University
Applied Physics Laboratory
Laurel, MD 20723

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

44997.5-PH-QC

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This is the final report for an augmentation grant to investigate a linear optics approach to quantum computing. The main results of the study include a demonstration of a CNOT logic gate, a source of single photons on demand, a quantum memory device for photonic qubits, a small-scale circuit for photonic qubits, and a quantum error correction. The elimination of failure events using the quantum Zeno effect was proposed and is being investigated in a follow-on grant.

14. SUBJECT TERMS

quantum computer photon logic

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

Additional patent applications:

Franson, J.D., Donegan, M.M., Fitch, M.J., Jacobs, B.C., and Pittman, T.B.
"Techniques for High Fidelity Quantum Computing",
patent application # 1911-1485

Pittman, T.B. Franson, J.D., and Jacobs, B.C.
"Techniques for Storing a Polarization State of a Single Photon for Retrieving on Demand During Quantum Computation"
patent application # 1905/1906-1485

Franson, JD., Jacobs, B.C., and Pittman, T.B.
"Techniques for Quantum Processing with Photons and the Zeno Effect"
Patent Application # 2018-0069

Franson, J.D., Jacobs, B.C., and Pittman, T.B.
"Nanocavities for Use in Quantum Information Processing"
Provisional application (number not available at this time)

FINAL PROGRESS REPORT

Foreword

This augmentation grant (DAAD19-03-1-0097) was for an investigation of a linear optics approach to quantum computing. At the time of the proposal, it had been suggested by Knill, Laflamme, and Milburn that quantum logic operations could be performed using linear optical elements, but their theoretical proposal did not appear to be feasible from an experimental point of view. As part of this proposal, we showed how quantum logic devices of this kind could be implemented in a practical way using polarization encoding. We went on to demonstrate many aspects of a linear optics approach to quantum computing, including quantum logic gates, a prototype quantum memory, a source of single photons on demand, small-scale quantum circuits, and quantum error correction. More recently, we showed how the probabilistic nature of these logic gates could be avoided by using the quantum Zeno effect to suppress the inherent failure events in an approach of this kind. As a result of this work, a hybrid optical approach of this kind appears to be one of the leading methods for a scalable approach to quantum computing.

This grant was intended to augment an earlier grant (DAAD19-02-0069) to increase the scope of the work. Both grants are for the same research topic and a similar report will be submitted for both, as suggested by the sponsor in previous years.

It should also be noted that this work is being continued as part of a follow-on grant for a consortium involving the Applied Physics Laboratory, the University of Illinois, the University of Queensland, and other international groups. Although this is a final report, it does not signify the end of this important area of research.

Statement of the problem

The ability to implement quantum logic gates using linear optical elements, additional photons known as ancilla, and measurements made on the ancilla is illustrated in Fig. 1. Here the two logical qubits are combined with the ancilla using a network of linear optical elements. Measurements made on the ancilla after the leave the device are used to determine the need for feed-forward correction on the output qubits. The operation is probabilistic in the sense that certain measurement outcomes indicate that the output qubits contain an uncorrectable error.

Although logic operations of this kind are very stable and relatively simple, there are a number of problems that must be addressed: What is the best way to perform logic operations with the smallest error rate? How can single photons be generated for use in these devices. Is it possible to develop quantum memories for photonic qubits. Can these techniques be used to build more complex circuits? Can quantum error correction be performed using linear optics techniques? Answers to most of these issues were found during the course of this work.

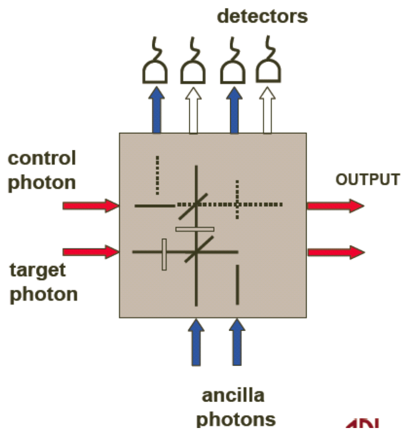


Fig. 1. Basic approach used in linear optics quantum computing.

Summary of the most important results

During the course of this work, we demonstrated a number of quantum logic operations, including a parity check, controlled CNOT gate, and full CNOT gate. Our CNOT gate is illustrated in Fig. 2. It consists of two polarizing beam splitters, two sets of detectors, and a pair of entangled ancilla photons. When one and only one photon is detected in each detector, we know that the correct logical output has been produced. This occurs ¼ of the time.

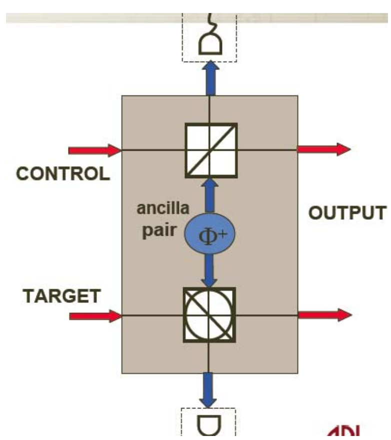
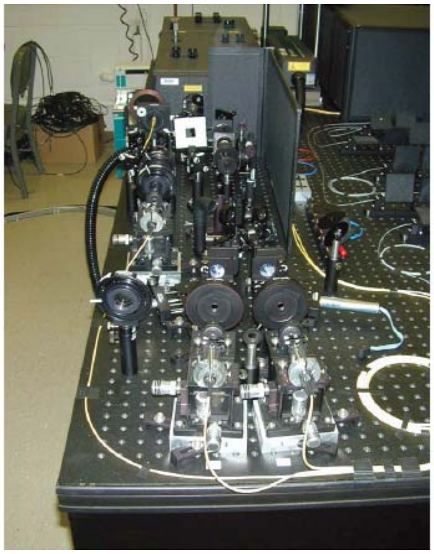


Fig. 2. The APL CNOT logic gate.

In order to demonstrate logic operations of this kind, it was necessary to develop a source of three indistinguishable photons. A photograph of the source and the first experimental demonstration of a CNOT logic gate for photonic qubits are show in Fig. 3.



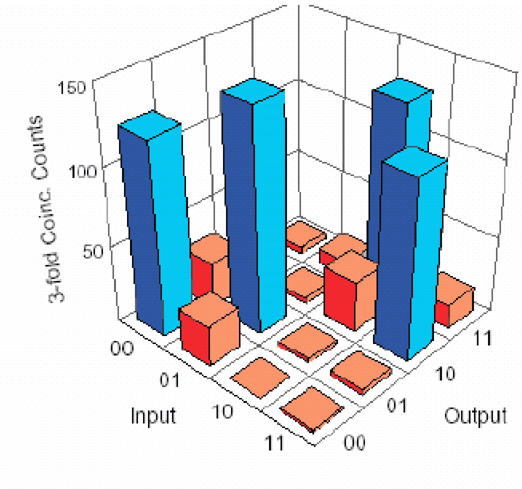


Fig. 3. Source of entangled photons and the first experimental demonstration of a CNOT gate for photonic qubits.

Another important logic device is a quantum encoder, which "copies" the value of a single input qubit into two output qubits. Our implementation of a quantum encoder and the corresponding experimental results are shown in Fig. 4.

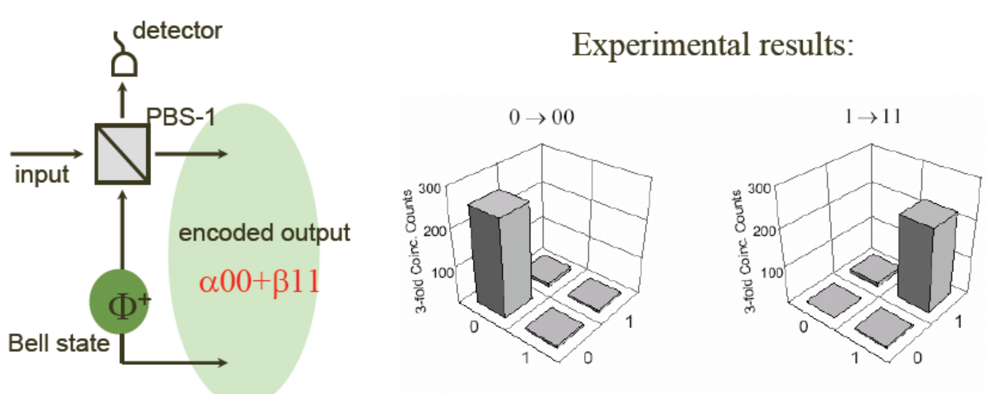


Fig. 4. Implementation of a quantum encoder and the corresponding expermental results.

One of the most important advantages of an optical approach to quantum computing is the fact that optical fibers or wave guides can be used to connect arbitrary quantum logic elements in analogy with the wires of a conventional computer. This capability is not a feature of most other approaches, such as ion traps. Fig. 5 shows our demonstration of the first quantum circuit using photonic qubits, which shows that logic devices can, indeed, be connected in this way. This circuit utilizes two XOR logic gates to calculate the parity of three arbitrary input qubits.

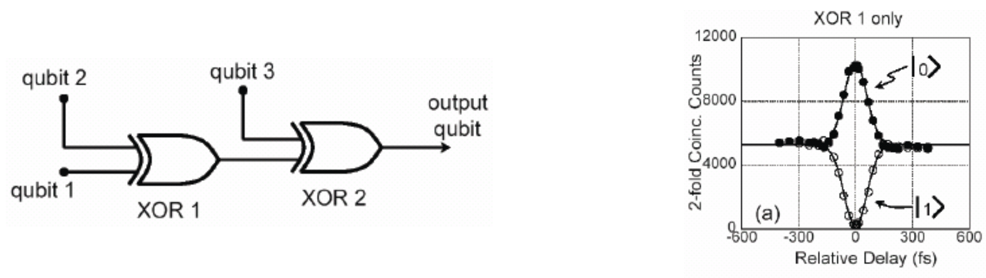


Fig. 5. First demonstration of a small-scale quantum circuit using linear optical elements and connections based on optical fibers.

Another important requirement for the development of a quantum computer is the ability to perform quantum error correction. In a linear optics approach, by far the most common error source is the accidental measurement of the value of a qubit. This type of error can be corrected using the encoding illustrated in Fig. 6 along with our implementation of it. The experimental results from this experiment are illustrated in Fig. 7.

$$|0\rangle \rightarrow |0_L\rangle = (|00\rangle + |11\rangle)$$
$$|1\rangle \rightarrow |1_L\rangle = (|01\rangle + |10\rangle)$$

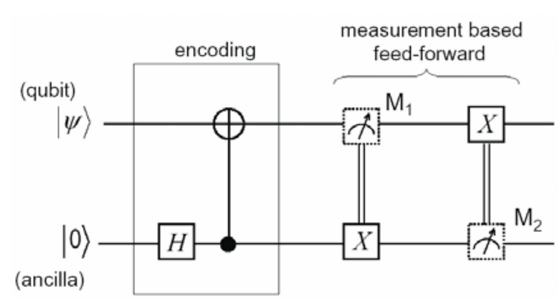


Fig. 6. Parity encoding used to correct for arbitrary z-measurement errors.

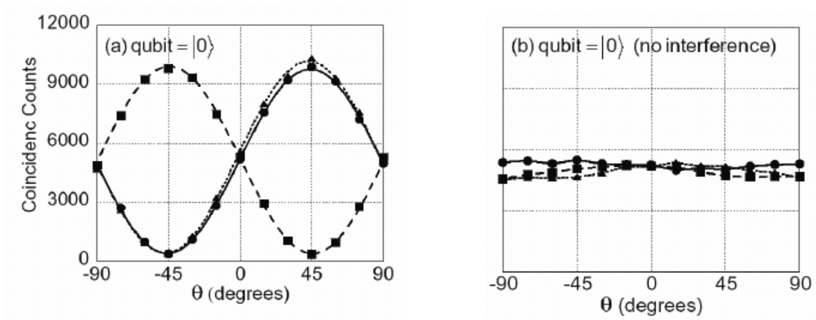


Fig. 7. Experimental results from the first demonstration of quantum error correction using photonic qubits.

In order for any optical approach to quantum computing to be practical, it will be necessary to have an efficient source of single photons on demand. As part of this grant, we developed the single-photon source shown in Fig. 8. Here parametric down-conversion is used to generate a pair of photons. The detection of one member of the pair indicates that the other photon is present with nearly 100% probability. A high-speed switch is then used to store the remaining photon in an optical storage loop until it is needed, at which time it can be switched back out of the loop.

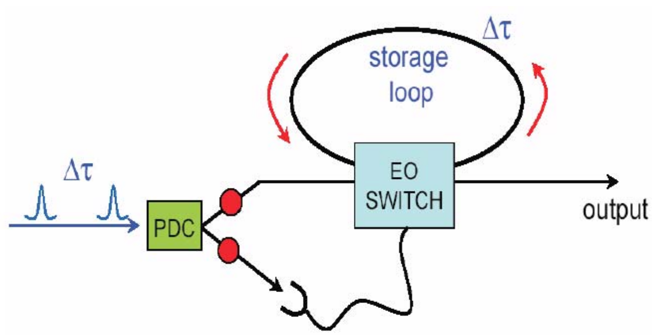


Fig. 8. Single-photon source based on parametric down-conversion and storage of a heralded photon in an optical storage loop.

We have also demonstrated a single-photon memory device based on a similar storage technique. Both of these applictions are limited, however, by the performance of the optical switch. Commercially-available switches are not designed for single-photon use or low loss. This prompted us to begin the development of a more efficient switch

for use in single-photon applications. Some of the preliminary results from this switch are illustrated in Fig. 9.

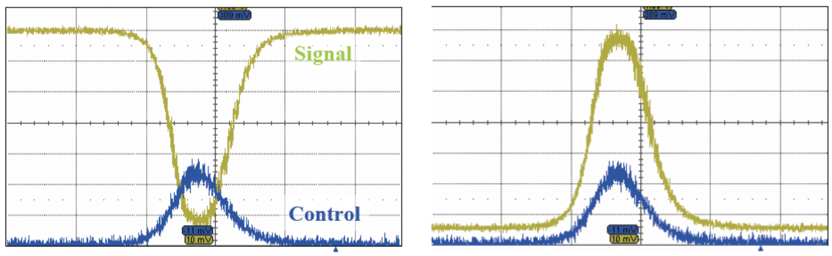


Fig. 9. Preliminary results from an all-optical switch designed for use with single photons.

Although all of the above results are very promising, the remaining difficulty with a linear optics approach to quantum computing is the fact that the logic operations are probabilistic. There are several ways to overcome this difficulty, including the use of cluster states. We are investigating a different solution based on the quantum Zeno effect, in which the occurrence of a random event can be suppressed by frequent observations to determine whether or not it has occurred, as illustrated in Fig. 10.

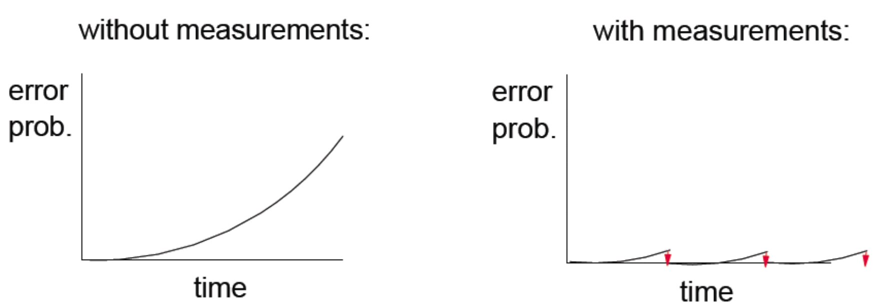


Fig. 10. Suppression of a random error by using the Zeno effect.

All of the failure events in our CNOT gate of Fig. 2 are due to the emission of two photons into the same output path. This can be suppressed using the quantum Zeno effect if two-photon absorbing atoms are present in all of the output paths. Roughly speaking, the atoms continuously "watch" for the presence of two photons, which is sufficient to prevent two photons from ever emerging into the same path. We are currently in the process of developing Zeno gates of this kind by utilizing small resonant cavities to enhance the rate of two-photon absorption compared to the single-photon absorption rate, as illustrated in Fig. 11.

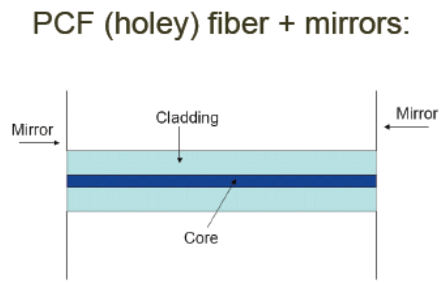


Fig. 11. Small mode volume cavity fabricated from a hollow-core fiber with mirrors on the ends.

In summary, this work has demonstrated many important aspects of a linear optics approach to quantum computing. Combined with the quantum Zeno effect, this approach has many potential advantages for the construction of a full-scale quantum computer.

Publications

<u>Papers published in peer-reviewed journals</u>

"Perturbation Theory for Quantum-Mechanical Observables", J. D. Franson and M. M. Donegan, Physical Review A **65**, 052107-1 to 052107-8 (2002).

"Dispersion Cancellation and Non-Classical Noise Reduction for Large-Photon-Number States", M. J. Fitch and J. D. Franson, Physical Review A **65**, 053809-1 to 053809-7 (2002).

"Demonstration of Nondeterministic Quantum Logic Operations Using Linear Optical Elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Physical Review Letters **88**, 257902-1 to 257902-4 (2002).

"High-Fidelity Quantum Logic Operations Using Linear Optical Elements", J. D. Franson, M. M. Donegan, M. J. Fitch, B. C. Jacobs, and T. B. Pittman, Physical Review Letters **89**, 137901-1 to 137901-4 (2002).

"Demonstration of Feed-Forward Control for Linear Optics Quantum Computation", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Physical Review A **66**, 052305-1 to 052305-7 (2002).

"Quantum Relays and Noise Suppression Using Linear Optics", B. C. Jacobs, T.

B. Pittman, and J. D. Franson, Physical Review A **66**, 052307-1 to 052307-6 (2002).

"Single Photons on Pseudo-Demand from Stored Parametric Down-Conversion", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Physical Review A **66**, 042303-1 to 042303-7 (2002).

"Cyclic Quantum Memory for Photonic Qubits, T. B. Pittman and J. D. Franson, Physical Review A **66**, 062302-1 to 062302-4 (2002).

"Experimental Progress in Linear Optics Quantum Computing", J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, Quantum Information and Control **3**, 553-562 (2003).

"Violation of Bell's Inequality with Photons from Independent Sources", T.B. Pittman and J.D. Franson, Physical Review Letters **90**, 240401-1 to 240401-4 (2003).

"Experimental Controlled-NOT Logic Gate for Single Photons in the Coincidence Basis", T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, Physical Review A **68**, 032316 (2003).

"Heralded Two-Photon Entanglement from Probabilistic Quantum Logic Operations on Multiple Parametric Down-Conversion Sources", T.B. Pittman, M.M. Donegan, M.J. Fitch, B.C. Jacobs, J.D. Franson, P. Kok, H. Lee, and J.P. Dowling, IEEE Journal of Selected Topics in Quantum Electronics **9**, 1478 (2003).

"Photon number resolution using time-multiplexed single-photon detectors", M.J. Fitch, B.C. Jacobs, T.B. Pittman, and J.D. Franson, Physical Review A **68**, 043814 (2003).

"Probabilistic Quantum Encoder for Single-Photon Qubits", T.B. Pittman, B.C. Jacobs, and J.D. Franson, Physical Review A **69**, 042306 (2004).

"Generation of Entangled Ancilla States for use in Linear Optics Quantum Computing", J.D. Franson, M.M. Donegan, and B.C. Jacobs, Physical Review A **69**, 052328 (2004).

"Photon Exchange Interactions and Quantum Information Processing", J.D. Franson, Phys. Rev. A **70**, 054301 (2004).

"Quantum Computing using Single Photons and the Zeno Effect", J.D. Franson, B.C. Jacobs, and T.B. Pittman, Phys. Rev. A **70**, 062302 (2004).

"Photon-number-resolving detection using time-multiplexing", D. Achilles, C.

Silberhorn, C. Śliwa, K. Banaszek, I.A. Walmsley, M.J. Fitch, B.C. Jacobs, T.B. Pittman, and J.D. Franson, Journal of Modern Optics **51**, 1499 (2004).

"Heralding single photons from pulsed parametric down-conversion", T.B. Pittman, B.C. Jacobs, and J.D. Franson, Optics Communications **246**, 545 (2004).

"Towards Scalable Linear-Optical Quantum Computers", J.P. Dowling, J.D. Franson, H. Lee, and G.J. Milburn, Quantum Information Processing **3**, 205 (2004).

"Demonstration of quantum error correction using linear optics", T.B. Pittman, B.C. Jacobs, and J.D. Franson, Phys. Rev. A **71**, 052332 (2005).

"Experimental Demonstration of a Quantum Circuit using Linear Optics Gates", T.B. Pittman, B.C. Jacobs, and J.D. Franson, Physical Review A **71**, 032307 (2005).

"Heralding Single Photons from Pulsed Parametric Down-Conversion", T.B. Pittman, B.C. Jacobs, and J.D. Franson, Optics Communications **246**, 545-550 (2005).

Papers published in conference proceedings:

"Experimental Demonstration of Quantum Logic Operations Using Linear Optical Elements", J.D. Franson, B.C. Jacobs, and T.B. Pittman, Proceedings of the IV Adriatico Research Conference on Quantum Interferometry, Trieste, Italy, 11-15 March, 2002 (Fortschr. Phys. **51**, 369-378, 2003). (Invited)

"Dispersion cancellation and non-classical noise reduction for large photon-number states", J. D. Franson and M. J. Fitch, Proceedings of the Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002 (Optical Society of America, Washington).

"Demonstration of non-deterministic quantum logic operations using linear optical elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Proceedings of the Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002 (Optical Society of America, Washington).

"Progress in Linear Optics Quantum Computing", J. D. Franson, M.M. Donegan, M.J. Fitch, B. C. Jacobs, and T.B. Pittman, Proceedings of the 6th International Conference on Quantum Communication, Measurement, and Computing, J.H. Shapiro and O. Hirota, Eds., Boston, MA, 22-26 July, 2002 (Rinton Press).

"Experimental Work Towards Linear Optics Quantum Computing: Three-Photon

Interference Experiments", T.B. Pittman and J.D. Franson, to appear in the Proceedings of the 8th International Conference on Squeezed States and Uncertainty Relations, Puebla, Mexico, 9-13 June, 2003. (Invited).

"Periodic Single-Photon Source and Quantum Memory", T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, to appear in the Proceedings of the SPIE Annual Meeting, San Diego, CA, 3-8 August, 2003.

"Quantum Logic using Linear Optics", J.D. Franson, B.C. Jacobs, and T.B. Pittman, to appear in *Quantum Communications and Cryptography*, A. Sergienko, ed. (Dekker).

"Simple Circuit of Linear Optics Logic Gates", T.B. Pittman, B.C. Jacobs, and J.D. Franson, to appear in the proceedings of the SPIE conference, Denver, CO, August 5, 2004.

Papers presented at meetings but not published:

"High Resolution Quantum Optics Applied to Metrology and Clocks", M. J. Fitch and J. D. Franson, 32nd Winter Colloquium on the Physics of Quantum Electronics, Snow Bird, UT, 6-19 January, 2002. (Invited)

"Demonstration of Non-deterministic Quantum Logic Operations using Linear Optical Elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, 32nd Winter Colloquium on the Physics of Quantum Electronics, Snow Bird, UT, 6-19 January, 2002. (Invited)

"Experimental Demonstration of Quantum Logic Operations using Linear Optical Elements", J. D. Franson, B. C. Jacobs, and T. B. Pittman, 4th Adriatico Research Conference on Quantum Interferometry, Trieste, Italy, 11-15 March 2002. (Invited)

"Demonstration of Non-Deterministic Quantum Logic Operations using Linear Optical Elements", B. C. Jacobs, T. B. Pittman, and J. D. Franson, Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society, Williamsburg, VA, 28 May - June 1, 2002.

"Dispersion Cancellation and Nonclassical Noise Reduction for Large Photon-Number States", Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002.

"Demonstration of Non-deterministic Quantum Logic Operations Using Linear Optical Elements", T. B. Pittman, B. C. Jacobs, and J. D. Franson, Quantum Electronics and Laser Science Conference, Long Beach, CA, 19-24 May, 2002.

“Demonstration of Probabilistic Quantum Logic Operations Using Linear Optics”, J. D. Franson, B. C. Jacobs, and T. B. Pittman, 6th International Conference on Quantum Communication, Measurement, and Computing, Cambridge, MA, 22-26 July, 2002.

“Quantum Logic Operations Using Linear Optical Elements”, J. D. Franson, Nonlinear Optics Conference, Maui, Hawaii, 29 Jul.-2 Aug., 2002. (Invited)

“Quantum Computing Using Linear Optics”, J. D. Franson, B. C. Jacobs, and T. B. Pittman, Feynman Festival Conference, College Park, MD, 23 -28 Aug., 2002. (Invited)

"Quantum Non-Demolition Measurements and Quantum Relays Using Linear Optics", B.C. Jacobs, T.B. Pittman, and J.D. Franson, OSA ANNUAL MEETING, Orlando, FL, September 30, 2002.

“Single-Photon Source and Quantum Memory”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, Optical Society of America Annual Meeting, Orlando, FL, October 3, 2002.

“Progress in Linear Optics Quantum Computing”, J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, 33rd Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT, 5-9 January, 2003. (Invited).

“Demonstration of Quantum Logic Operations Using Linear Optical Elements”, B.C. Jacobs, M.M. Donegan, M.J. Fitch, T.B. Pittman, and J.D. Franson, U.S.-Australia Workshop on Solid State and Optical Approaches to Quantum Information Science, Sydney, Australia, 7 January 2003. (Invited)

“Need for High Efficiency Photon-Number Resolving Detectors in Linear Optics Quantum Computing”, T.B. Pittman, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and J.D. Franson, NIST-ARDA Workshop on single-photon detectors, Gaithersburg, MD, March 31, 2003.

“Experimental Controlled-NOT Logic Gate for Single Photons”, T.B. Pittman, M.J. Fitch, B.C. Jacobs, and J.D. Franson, Gordon Research Conference on Quantum Information Science, Ventura, CA, March 23-28, 2003.

“Quantum Computation with Linear Optics”, M.J. Fitch, M.M. Donegan, T.B. Pittman, B.C. Jacobs, and J.D. Franson, 17th International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, Orlando, FL, 21 April 2003. (Invited).

“High-Fidelity Quantum Logic Operations and Entangled Ancilla States”, J.D. Franson, M.M. Donegan, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

“Improved Single-Photon Detector Performance, M.J. Fitch, M.M. Donegan, B.C. Jacobs, T.B. Pittman, and J.D. Franson, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

“Quantum Logic Operations in Optical Fibers”, B.C. Jacobs, T.P. Pittman, M.J. Fitch, and J.D. Franson, Quantum Electronics and Laser Science Conference, Baltimore, MD, June 1-6, 2003.

“Single-Photon Source and Quantum Memory”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, “Single-Photon Source and Quantum Memory”, SPIE Quantum Communications and Quantum Imaging, San Diego, CA, August 5, 2003. (Invited)

“Violation of Bell’s Inequality with Photons from Independent Sources”, T. B. Pittman and J.D. Franson, 87th OSA Annual Meeting, Tucson, AZ, October 5-9, 2003.

“Linear Optical Quantum Computing”, J.D. Franson, M.J. Fitch, B.C. Jacobs, and T.B. Pittman, 87th OSA Annual Meeting, Tucson, AZ, October 5-9, 2003. (Invited).

“Linear Optics Quantum Computing”, 34th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 4-8, 2004 (Invited).

"Incremental Information Extraction from Grover's Algorithm", B.C. Jacobs and J.D. Franson, Winter International Symposium on Information and Communication Technologies, Mexico, January 5, 2004.

“Hybrid Optical Approach to Quantum Computing”, J.D. Franson, Conference on Quantum Information with Atoms, Ions, and Photons, La Thuile, Italy, March 6-12, 2004 (Invited).

“Quantum Information Processing with Linear Optics and the Zeno Effect”, J.D. Franson, Workshop on Quantum Information Processing with Linear Optics, Erlangen, Germany, April 14-16, 2004 (Invited).

“Hybrid Optical Approach for Optical Quantum Computing”, J.D. Franson, B. C. Jacobs, and T.B. Pittman, CLEO/IQEC conference, San Francisco, CA, May 17, 2004.

“Experimental Quantum Encoder for Single-Photon Qubits”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, CLEO/IQEC conference, San Francisco, CA, May 17, 2004.

“Quantum Information Processing Using Photons”, J.D. Franson, 35th Meeting of

the Division of Atomic, Molecular and Optical Physics, Tucson, AZ, May 27, 2004 (Invited).

“Quantum Computing using Single Photons and the Zeno Effect, J.D. Franson, B.C. Jacobs, and T.B. Pittman, Quantum Information and Quantum Control Conference, Toronto, Canada, July 19, 2004.

“Quantum Computing using linear optics and the Zeno effect, J.D. Franson, B.C. Jacobs, and T.B. Pittman, Seventh International Conference on Quantum Communication, Measurement, and Computing, Glasgow, Scotland, July 28, 2004 (Invited.)

“Simple Circuits of Linear Optics Quantum Logic Gates”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, SPIE Quantum Communications and Quantum Imaging II, Denver, CO, August 5, 2004. (Invited)

“Quantum computing using single photons and the Zeno effect”, J.D. Franson, Second Feynman Festival, College Park, MD, August 25, 2004 (Invited).

“Quantum Computing Using Linear Optics and the Zeno Effect”, ERATO Conference on Quantum Information Sciences 2004, Tokyo, Japan, September 1-6, 2004 (Invited).

“Simple Quantum Circuit of Linear Optics Gates”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, Optical Society of America Annual Meeting, Rochester, NY, October 11, 2004.

“Linear Optics Quantum Computing”, J.D. Franson, 35th Winter Colloqium on the Physics of Quantum Electronics, Snowbird, UT, January 2, 2005 (Invited).

“Heralding Single Photons from Pulsed Parametric Down-Conversion”, T.B. Pittman, B.C. Jacobs, and J.D. Franson, 35th Winter Colloqium on the Physics of Quantum Electronics, Snowbird, UT, January 2, 2005.

“Recent progress in linear optics quantum computing”, J.D. Franson, Workshop on Quantum Information Processing with Linear Optics (QUIPROLO II), Bristol, UK, March 29-31, 2005. (Invited)

"Single-Photon Switches for Quantum Information Processing", B.C. Jacobs, T.B. Pittman, and J.D. Franson, CLEO/QELS 05, Baltimore, MD, May 23, 2005.

Manuscripts submitted but not yet published:

“Discrepancies in the covariant formulation of quantum optics and quantum electrodynamics due to entanglement”, J.D. Franson, submitted to Physical Review Letters.

“Entangled Photon Holes”, J.D. Franson, submitted to Physical Review Letters.

Scientific personnel

J.D. Franson – Principal investigator

T.B. Pittman – staff scientist

B.C. Jacobs – staff scientist

R. Sova – staff scientist

S. Hendrickson – graduate student

Report of Inventions

The following patents were awarded by the U.S. Patent Office:

“Optical Method for Quantum Computing”, J.D. Franson, U.S. patent #6,678,450, 13 January, 2004.

“Techniques for Performing Logic Operations using Quantum States of Single Photons”, T.B. Pittman, J.D. Franson, and B.C. Jacobs, U.S. patent #6,741,374, 25 May, 2004.

The following patent applications were submitted:

"Techniques for Quantum Processing with Photons and the Zeno Effect"

"Techniques for Storing a Polarization State of a Single Photon for Retrieving on Demand during Quantum Computing"

"Techniques for High Fidelity Quantum Computing"

Bibliography – see publications

Appendices - none